

Chromaticity of unique white in illumination mode

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Abstract: The chromaticity of unique white viewed in illumination mode and under dark adapted conditions was investigated for 3 luminance levels (200, 1000 and 2000 cd/m²) using a unique white setting method. Unique white was found to encompass a rather large region in color space located slightly below the blackbody locus and centered around a CCT of 6600 K. Luminance level was found to have no significant effect on the mean unique white chromaticity. The high and low end points of the CIE class A and B white regions respectively under- and overestimate the chromaticity region perceived as white. Agreement along the Duv direction was quite good. However, another Duv related limit associated with *white lighting* ($|Duv| \leq 5.4 \times 10^{-3}$) was found to be on the small side, especially for chromaticity values below the blackbody locus. The results for unique white viewed in illumination mode were compared to those reported for object mode presentation. Overall they were very comparable, although a statistical analysis does show a (just) significant effect of stimulus presentation mode for high (il)luminance levels. However, no such effect could be established at the individual observer level. Therefore, it was concluded that unique white chromaticity is essentially the same for both illumination and object mode stimulus presentation, at least under dark adapted viewing conditions.

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1. Introduction

Although important in lighting and color science, "*white*" remains an ambiguous concept: It can refer to physical properties of radiation ("*white light*": illumination with a wide variety of correlated color temperatures (CCT)) and surfaces ("*white object*": usually denoting a high, non-selective spectral reflectance, but often complicated by the potential presence of fluorescent whitening agents) or to psychophysical properties of experience ("*neutral* or *unique white*": denoting a lack of hue sensation, due to balancing of the visual system's opponent channels) [1].

In addition to this categorical ambiguity, "*white*" is also plagued with uncertainty with regard to its chromaticity. As already mentioned, the term "*white lighting*" is often used to denote illumination with chromaticity—on or off the blackbody locus—corresponding to a wide range of CCTs, despite the fact that not all "*white objects*" illuminated by them *look (the same) "white"*. Even for those chromaticity values that result in a *neutral white* appearance, there is quite a bit of disagreement among various psychophysical studies in literature. For an extensive overview see Smet, Deconinck and Hanselaer [2]. Also, note that *unique white* does not necessarily refer to the most *preferred white*, which can have a slight tint to it and is likely to be illuminance (cfr. Kruithof's curve), application and region dependent.

The mode of appearance of a stimulus, i.e. the perceived nature of the stimulus, can have a profound effect on its color appearance [3]. Several modes have been defined, the most important being: *object mode* whereby color is interpreted as a part of a reflective surface (object *surface mode*) or the bulk of a translucent or transparent medium (object *volume mode*), *illuminant mode* whereby color is interpreted as belonging to a source of light, *illumination mode* whereby color is thought to be the results of illumination, rather than belonging to the illuminated objects themselves and *film* or *aperture mode* whereby color is perceived to be unconnected to any object (or light source) [4].

In a recent study investigating the chromaticity of white in illumination mode, Rea and Freyssinier [5] reported negative and positive Duv values for CCTs respectively below and above 4000 K. In a similar study, Ohno and Fein [6] reported strictly negative Duv for the chromaticity of white. Although both studies used an illumination mode, the discrepancy between the two results is probably due to the specifics of the viewing conditions. Rea and Freyssinier [5] used an experimental setup whereby the stimuli lacked a background and had a field of view of nearly 180°, in which case peripheral effects and stimulus adaptation become important. Ohno and Fein [6] provided a more natural viewing condition consisting of colored objects in a scene, but color rendering issues might have affected the results. No specific CCT value(s) were specified as both studies actually report a line of whites as a result of the experimental procedure [7] that ignored potential CCT-dependent differences in the appearance of "*white*".

In Smet, Deconinck and Hanselaer [2], the chromaticity of unique white was investigated with the stimulus presented in object mode. Unique white was found to encompass quite a substantial region in the CIE $u'v'$ chromaticity diagram, with its center located slightly below the blackbody locus (i.e. negative Duv) and corresponding to a CCT of around 6000 K.

As the viewing mode can substantially impact the color appearance of a stimulus [3], the results reported in Smet, Deconinck and Hanselaer [2] for the chromaticity of white in object mode are extended to the illumination mode in a series of *unique white* adjustment

experiments. Unique white settings are determined at three luminance levels of 200, 1000 and 2000 cd/m^2 (corresponding to illuminance values of respectively 740 lx, 3700 lx and 7400 lx) and the results are compared with those obtained with stimulus presentation in object mode.

2. Methods

2.1 Experimental setup

The same setup was used as in Smet, Deconinck and Hanselaer [2], where a data projector was used to generate a real 3D stimulus. However, instead of only changing the pixels associated with the geometric projection of the 3D cube, an *illumination* type stimulus was generated by projecting a *spotlight* like image onto a 3D scene composed of a real 3D cube (8.5 cm x 8.5 cm x 8.5 cm) and a small painted wooden artist model (see Fig. 1). Both scene objects have an approximately non-selective spectral reflectance ($\beta \approx 0.85$). The presence of the wooden statue enhanced the illumination mode of the stimulus. No colored objects were added to the scene to ensure that color rendering issues would not contribute to the results.

The pixels associated with the background (the area outside of the spotlight) were set to black (cfr. baseline dark adaptation condition). The CIE 1976 $u'v'$ chromaticity and luminance are respectively, $(u'_{10}v'_{10}) = (0.2759, 0.2344)$ and $Y_{10} = 0.40 \text{ cd/m}^2$.

The viewing booth was calibrated which allowed test subjects to adjust the chromaticity of the spotlight stimulus along 8 directions in the CIE 1976 $u'v'$ diagram using the keys of the numeric pad on a regular black keyboard. One key-press changed the chromaticity in the selected direction by 0.0006 (small enough to be not noticeable); by simultaneously pressing either the alt-, ctrl- or shift-key that step change could be increased by a factor of respectively 5, 10 and 50.

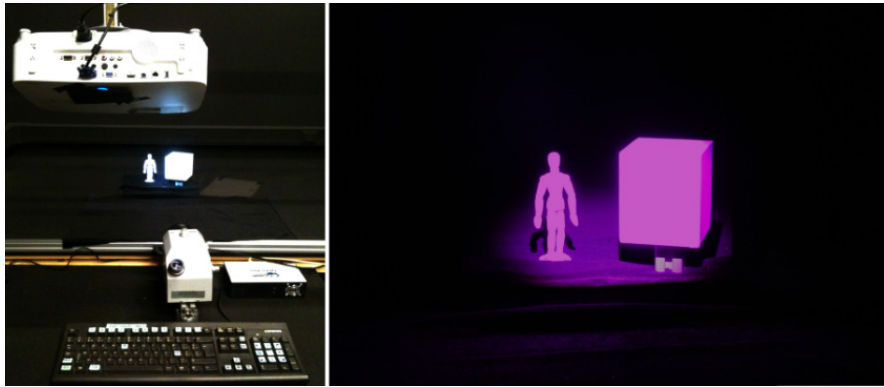


Fig. 1. Experimental Setup. Left: full setup. Right: view by an observer focused on the stimulus.

The scene-observer distance was approximately 100 cm, providing a field of view (FOV) of 5.7° for the cube and 15.5° for the spotlight. As the FOV of both targets was larger than 4° , all chromaticity values were determined using the CIE 1964 observer from calibrated spectral measurements obtained with an Ocean Optics QE65000 Pro spectrometer.

The 10° CIE 1976 u',v' chromaticity coordinates and luminance measured on the top left corner of the 3D cube when illuminated with the data projector's primaries at maximum were: $R = (0.4298, 0.5334, 1743 \text{ cd/m}^2)$, $G = (0.1561, 0.5709, 5989 \text{ cd/m}^2)$ and $B = (0.1343, 0.2235, 1077 \text{ cd/m}^2)$. A stable output of the data projector was ensured by a warm-up period of minimum 1 hour prior to the start of the visual experiments.

2.2 Observers

Thirteen observers (6 female, 7 male) with normal color vision as determined by the Ishihara 24 plate test, participated in the experiments. Their average age was 31 ± 8 years. Note that the same observers were used as those in the object mode experiments reported in [2].

2.3 Experimental procedure

Unique white was investigated in illumination mode in a series of experiments under dark adaptation conditions for 3 stimulus intensities: 200 cd/m², 1000 cd/m² and 2000 cd/m². Stimulus intensities were measured at the 3D cube. They correspond to approximate illuminance levels of respectively: 740 lx, 3700 lx and 7400 lx.

Observers were asked to adjust the chromaticity of the spotlight illuminated scene along the axes of the CIE 1976 $u'v'$ diagram until it appeared *neutral white*, i.e. until it showed neither red, nor green, nor yellow, nor blue tint, nor could it be classified as either warm or cold white.

For each observer, 7 random starting stimuli were generated, fulfilling two conditions: 1) excitation purity was within the projector gamut, but outside the CIE class *A* and *B* white regions [8]; 2) the dominant wavelength of the starting stimuli were uniformly distributed. The starting stimuli generated for the three luminance levels were pooled and subsequently randomized. Six additional training stimuli were added. In total, the observers had to make 27 successive unique white settings in a single session, lasting approximately 45 minutes. Repeats to assess intra-observer variability were performed on a separate day.

When observers were satisfied with their neutral white setting, it was spectrally measured and the 10° CIE 1976 $u'v'$ chromaticity coordinates were calculated.

3. Results and discussion

This section starts with a discussion of the results on unique white settings with the stimulus presented in illumination mode and concludes with a statistical analysis comparing the unique whites obtained in illumination mode (present study) and object mode (as reported in [2]).

3.1 Illuminant mode

In the experiment, observers had to adjust the color of the spotlight stimulus until it appeared neutral white. Three (il)luminance levels were investigated. The results are shown in Figs. 2(a)-2(c). The colored circles show the unique white settings of each individual observer. The colored ellipses are the observer 1-Standard Deviation (1-SD) ellipses and are a measure of the test subject's intra-observer variability. The average SD ellipse – a measure for the average intra-observer variability – and the SD-ellipse obtained for the average observer unique settings – a measure for the inter-observer variability – are respectively plotted as a dashed and solid black line in Fig. 2. Note that the 3-SD ellipses were plotted for clarity. The size of the major and minor axis, the center, the angle of rotation and the area (absolute and relative to luminance $Y = 2000$ cd/m²) of the 1-SD ellipses are given in Table 1. It is clear, both from Fig. 2 and Table 1, that the intra- and inter-observer variations are quite large, which is consistent with the results for unique white settings in object mode under dark adapted conditions reported in Smet, Deconinck and Hanselaer [2] and the unique whites reported in other literature [9–11]. The intra-observer variability is also slightly larger than the inter-observer variability, as can be readily seen by comparing the size of the SD ellipses in Fig. 2 or Table 1. A comparison of the 3-SD elliptical regions (cfr. 99% confidence regions for unique white) with the CIE class *A* and *B* white regions (see Fig. 1) shows the latter to be in quite good agreement along a direction roughly perpendicular to the blackbody locus. However, with regards to their extent along the blackbody locus, the low and high color temperature limits of the CIE class *A* and *B* white regions are clearly over- and respectively underestimating the chromaticity area perceived as white under dark adapted viewing

conditions. Finally, in agreement with the results of Chauhan, Perales, Xiao, Hird, Karatzas and Wuerger [12] and those for the object mode stimulus presentation reported in Smet, Deconinck and Hanselaer [2], the major axis of the intra- and inter-observer SD ellipse is directed approximately along the blackbody locus.

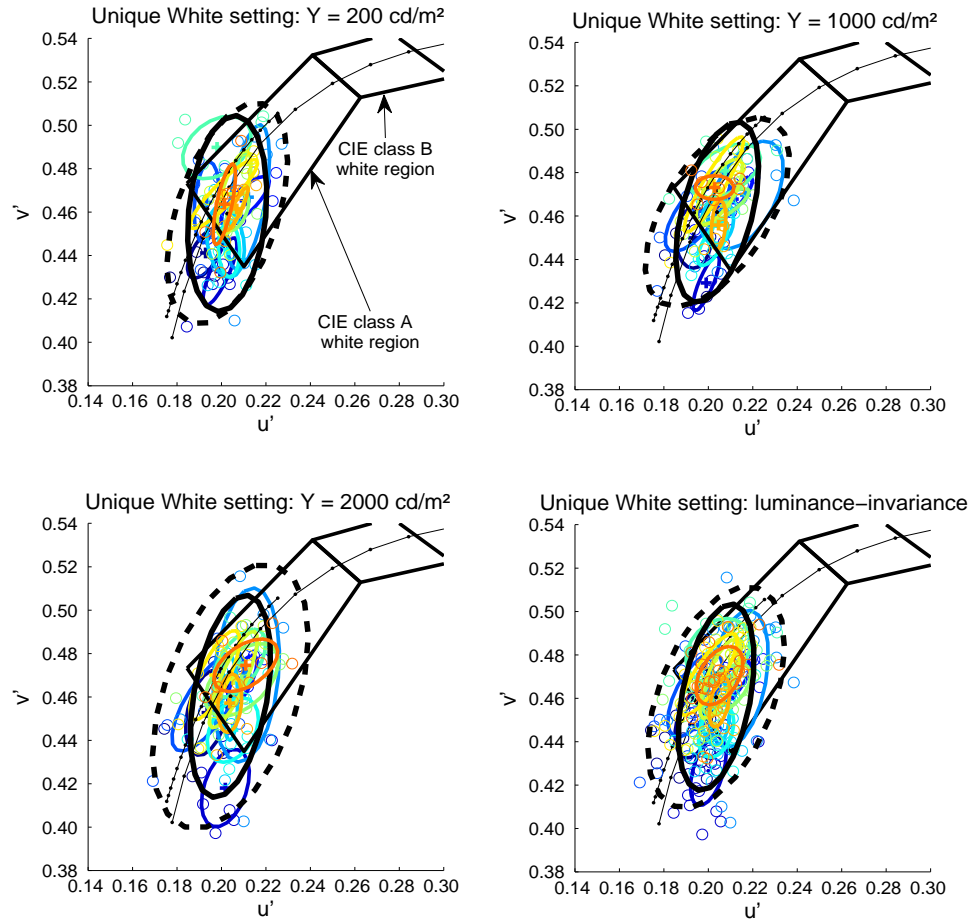


Fig. 2. Unique whites settings and the associated standard deviation ellipses for each observer (each color represents data of one observer): (a) 200 cd/m^2 , (b) 1000 cd/m^2 , (c) 2000 cd/m^2 and (d) luminance invariance assumed. The average 3-SD-ellipse (dashed black line) – a measure for the average intra-observer variability – and the 3-SD-ellipse of the average observer unique settings (solid black line) – a measure of the inter-observer variability – are also plotted. Finally, the CIE class A and B white regions are also shown, along with the blackbody and daylight loci (thin black solid curves).

As can be seen from Table 1, the centers of the SD-ellipses for the 200 cd/m^2 , 1000 cd/m^2 and 2000 cd/m^2 luminance levels are almost identical. The mean and maximum observed CIE color differences $\Delta E_{u',v'}$ were respectively 0.0010 ± 0.0007 and 0.0028 , and correspond approximately to a 1 and 3 steps MacAdam ellipse.

Table 1. Intra (average) and inter observer variability ellipses for the adjustment method.

Luminance (cd/m ²)	type	Major axis	Minor axis	u'_{center}	v'_{center}	Rotation θ (°)	Area (10 ⁻⁴) / %
200	intra	0.0177	0.0076	0.2026	0.4593	72	4.25 / 64
	inter	0.0151	0.0058	0.2026	0.4593	85	2.76 / 101
1000	intra	0.0163	0.0079	0.2040	0.4618	59	4.05 / 61
	inter	0.0143	0.0053	0.2040	0.4618	76	2.36 / 87
2000	intra	0.0212	0.0100	0.2040	0.4603	71	6.68 / 100
	inter	0.0157	0.0055	0.2040	0.4603	80	2.72 / 100
Invariance	intra	0.0179	0.0087	0.2035	0.4605	69	4.87 / 73
	inter	0.0145	0.0051	0.2035	0.4605	80	2.35 / 86

A doubly multivariate repeated measures MANOVA, with luminance level as the within-subjects factor, confirmed that there was indeed no (il)luminance dependent effect: (*Wilk's Lambda* = 0.456, $F(4,9) = 2.682$, $p = 0.101$, partial eta squared (η^2) = 0.544). This is in agreement with the results of Hurvich and Jameson [1] and Walraven and Werner [13], who also found unique white to be luminance-invariant. As a consequence the raw unique white settings of the different luminance levels were pooled and the 1-SD intra and inter-observer variability ellipses were calculated. The results are plotted in Fig. 2 and reported in Table 1 and are indicated as “invariance”.

The correlated color temperature (CCT) and Duv values corresponding to the centers of the SD-ellipses are shown in Table 2 for the 3 luminance levels and the luminance invariant case. The maximum and minimum observed values and the standard errors (SE) for the ‘average observer’ are given as well. The CCT and Duv for the unique white settings of the individual observers are illustrated in Fig. 3. Note that reported CCTs and Duvs were calculated using the CIE 10° observer, in correspondence to the test stimuli chromaticities.

Table 2. Maximum and minimum of the CCT and Duv corresponding to the centers of the individual observer SD-ellipses and the CCT and Duv (and their standard errors, SE) for the average observer.

Luminance (cd/m ²)	Max CCT (K)	Min CCT (K)	Avg. observer CCT ± 1 SE (K)	Max Duv	Min Duv	Avg. observer Duv ± 1 SE
200	10002	5569	6758 ± 400	0.0123	-0.0117	-0.0045 ± 0.0019
1000	10701	5269	6491 ± 416	0.0025	-0.0126	-0.0046 ± 0.0014
2000	13154	5425	6583 ± 589	0.0043	-0.0184	-0.0053 ± 0.0016
Invariance	11091	5503	6609 ± 435	0.0041	-0.0143	-0.0048 ± 0.0016

From Table 2 and Fig. 3 it is clear that the average CCT is approximately that of typical daylight (D65), but that there are large individual differences, which is consistent with the unique whites and their ranges reported in literature [1, 2, 10, 11, 13–15].

With regard to the Duv values, several observations can be made. First, there are large individual differences. Second the range of Duv values extends beyond what is typically still considered “white light” as defined by the validity of the concept of CCT ($|\text{Duv}| \leq 5.4\text{e-}3$). In fact, the average Duv is only barely within the accepted limits. Thirdly, most observers had unique white settings with negative Duv values, in general agreement with the results obtained by Ohno and Fein [6], although they reported Duv values which are 2 to 3 times more negative. However, the results are not in agreement with those from Rea and Freyssinier [5], who reported positive Duv for CCTs above 4000 K. As mentioned in the introduction, differences in viewing context and adaptation state could be the reason for the observed discrepancies.

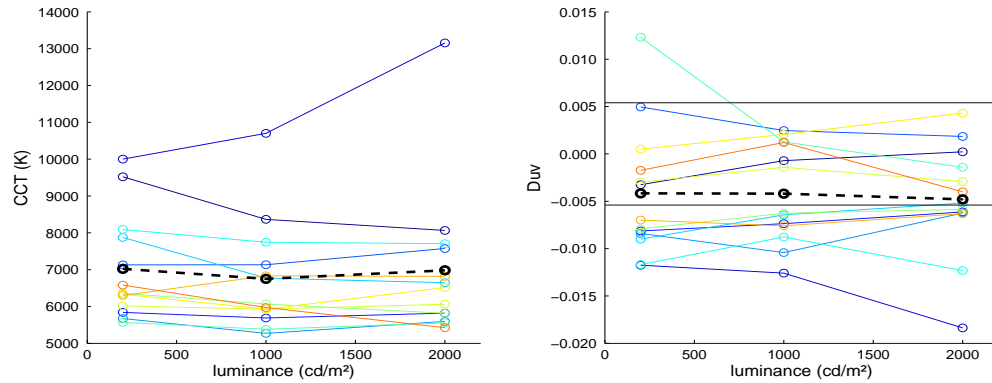


Fig. 3. CCT (a) and Duv (b) versus luminance level. Colored solid lines: individual test subjects. Black dashed lines: 'average' observer. Solid black lines in the Duv graph show the limits of what is typically still considered white light, i.e. chromaticity values for which the concept of CCT is valid: $|\text{Duv}| \leq 5.4 \times 10^{-3}$.

3.2 Unique white settings: illuminant mode versus object mode

A doubly multivariate repeated measures MANOVA with a three factor within-subjects design, was conducted with SPSS to investigate the influence of the stimulus presentation mode and luminance level on the unique white settings. The three Independent Variables (IV) are: IV1 = *luminance level*, IV2 = *stimulus presentation mode* and IV3 = *repeats*. The dependent variables (DV) are the CIE 1976 u^*v^* coordinates of the unique whites obtained during the experiments reported in this study and those in Smet, Deconinck and Hanselaer [2]. The assumption of multivariate normality for a doubly multivariate repeated measures MANOVA was checked with Mardia's test on multivariate skewness and kurtosis [16]. No significant ($p < 0.05$) violations were found for the main effects of presentation mode, luminance level and repeats. The results of the statistical analysis were as follows.

First, repeats had no significant effect (*Wilk's Lambda* = 0.097, $F(2,11) = 0.776$, $p = 0.722$, partial eta squared (η^2) = 0.903), indicating that start-point bias was successfully avoided. Also, no significant interactions with repeats were observed ($p < 0.05$).

A significant interaction was found between the main effects of luminance level and stimulus presentation mode (*Wilk's Lambda* = 0.176, $F(12,1) = 10.548$, $p = 0.002$, partial eta squared (η^2) = 0.824), indicating the chromaticity of unique white is different for each presentation mode depending on the (il)luminance (or vice versa).

Posthoc follow-up tests for the interaction showed that the effect of presentation mode on the chromaticity of the unique white was only significant for the 2000 cd/m^2 luminance level (*Wilk's Lambda* = 0.454, $F(2,11) = 6.602$, $p = 0.013$, partial eta squared (η^2) = 0.546), indicating that the effect is limited to high (il)luminance levels. Even after applying a Bonferroni correction, to account for the inflation of the *type-I* error due to the multiple MANOVAs, the effect remained significant ($p < 0.016$), although only barely. However, a series of doubly repeated measures MANOVAs, one for each observer and with stimulus presentation mode as the within-subjects factor and u^* , v^* as the DVs, showed a significant ($p < 0.05$) effect for only 2 of the 13 observers. No significant ($p < 0.004$) effect remained after a Bonferroni correction.

As reported in [2] and in subsection 3.1, the main effect of luminance was respectively significant and non-significant for the object and illumination stimulus presentation modes. Note that despite the significant effect for the mean unique white chromaticity for object mode, no significance could be established at the individual observer level, which lead to the postulation of a luminance invariant unique white chromaticity [2]. Assuming luminance invariance, a doubly multivariate repeated measures MANOVA showed no significant

difference between the unique whites obtained in both modes (*Wilk's Lambda* = 0.635, $F(2,11) = 3.235$, $p = 0.082$, partial eta squared (η^2) = 0.365). Indeed, both modes have their luminance invariant unique white located below the blackbody locus at similar Duv, resp. -0.0048 ± 0.0016 and -0.0065 ± 0.0012 and CCT, resp. $6609 \text{ K} \pm 435 \text{ K}$ and $5963 \text{ K} \pm 267 \text{ K}$.

It can therefore be concluded that given the results and the inter-observer variation present in this and former study ([2]) essentially no difference could be established between the chromaticity of unique white in illumination mode or object mode.

4. Conclusion

The chromaticity of unique white presented in illumination mode under dark adapted conditions was investigated using a stimulus adjustment method. Three luminance levels (200, 1000 and 2000 cd/m^2) have been used and the experiments have been performed by 13 color normal observers. The luminance levels corresponded to illuminance values of approximately to 740 lx, 3700 lx and 7400 lx respectively. Although the highest (il)luminance values are less common in many indoor lighting situations, they are nonetheless valuable from a color vision or color appearance modeling point of view [17].

In agreement with previous values and ranges reported in literature, large inter-observer differences for unique white chromaticity were found. Contrary to the line of whites reported by Rea and Freyssinier [5] and Ohno and Fein [6], unique white was found to encompass a two-dimensional region in color space located primarily below the blackbody locus and centered around 6600 K. Comparing the location and size of the inter-observer 3-SD ellipses (99% confidence region for unique white perception) showed that the high and low CCT ends of the CIE class A and B white regions respectively under- and overestimate the chromaticity region perceived as white. Quite good agreement was found along the Duv dimension. The unique whites obtained for the three (il)luminance levels were very similar: resp. $6758 \text{ K} \pm 400 \text{ K}$, $6491 \text{ K} \pm 416 \text{ K}$ and $6583 \text{ K} \pm 589 \text{ K}$. No significant difference could be established in a doubly multivariate repeated measures MANOVA with $u'v'$ as the dependent variables.

The results of the present study, with stimulus presentation in illumination mode, were compared with those with the stimulus presented in object mode (as reported in [2]). A significant interaction between (il)luminance level and presentation mode was found in a doubly multivariate repeated measures MANOVA. Posthoc follow-up tests showed the effect of presentation mode on the chromaticity of the unique white to be significant only for the 2000 cd/m^2 luminance level. Although these results suggest that for high (il)luminance levels the chromaticity of unique white in illumination mode is different from that in object mode, they were not supported by a series of repeated measures MANOVAs on the individual observer data. The chromaticity of unique white can therefore be considered, given the large variability, to be essentially the same in both the illumination and object mode.

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